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Direct Deposition of Low Resistance Thermally Stable Ohmic Contacts to *n*-SiC

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Abstract

Ni2Si Ohmic contacts were fabricated via pulsed laser deposition on n-SiC. The contacts' electrical, structural, compositional, and surface morphological properties were investigated as a function of annealing temperatures ranging from 700 to 950 °C. The as-deposited and 700 °C annealed contacts were non-Ohmic. Annealing at 950 °C yielded excellent Ohmic behavior, an abrupt void-free interface, and a smooth surface morphology. No residual carbon was present within the contact metallization or at the contact-SiC interface, and the contact showed no appreciable thickness increase as a result of the annealing process. Our results demonstrate that aside from maintaining the desirable electrical integrity associated with Ni and Ni/Si Ohmic contacts, the Ni2Si Ohmic contacts possessed improved interfacial, compositional, microstructural, and surface properties which are required for reliable high temperature and high power device operation.

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1. Introduction

SiC is an excellent candidate for high temperature and high power device applications because of its combination of electronic and thermal properties, namely, wide energy bandgap, high electric breakdown field, large saturated electron drift velocity, and high thermal conductivity [1-5]. Based on these properties, devices fabricated from SiC promise superior performance to that of present day devices. In order to realize this enhanced performance for the next generation of devices, low resistance, thermally stable, reliable metallizations for Ohmic contacts to SiC must be developed. Recently, there have been a considerable number of research efforts focused on the development of Ohmic contacts to *n*-SiC. As a result of these studies Ni-based Ohmic contacts have been suggested as superior candidates due to their reproducible low specific contact resistance, less than 5.0×10^{-6} Ω-cm^2, and good physical thermal stability at temperatures up to 500 °C [6–9]. The excellent electrical integrity of Ni-based Ohmic contacts is due to the formation of Ni-silicide after high temperature annealing at 950–1000 °C [4, 10–13]. Unfortunately, the formation of the Ni-silicide, with its desirable low specific resistance, is paralleled by several undesirable features. These features include broadening of the metal-SiC interface, a rough interface morphology heavily laden with Kirkendall voids, carbon segregation at the metal-SiC interface and/or throughout the metal layer, and substantial roughening of the contact surface [4, 11, 12, 14]. Therefore, even though Ni contacts possess excellent electrical properties, the features mentioned previously will lead to device reliability problems and ultimately cause device failure via contact degradation and/or wire bond failure after exposure to long term high power and high temperature device operational stresses.

Improved material properties, with respect to pure Ni contacts, have been demonstrated utilizing high temperature (950 °C) annealed Ni/Si multilayers on *n*-SiC [12, 15]. The principle of this approach involved high temperature annealing of discrete Si and Ni layers (Ni/Si and/or Si/Ni) on SiC to form Ni_2Si without decomposition of the SiC substrate, thereby eliminating the possibility of residual carbon accumulation and void formation. Results of this work showed that high temperature annealing caused the mutual diffusion of Si and Ni necessary to form the orthorhombic Ni_2Si phase; however, small amounts of residual carbon and interfacial voids were still present within the contact layer and at the contact-SiC interface. Thus, this approach limited but did not eliminate the SiC decomposition; consequently, contact-SiC interdiffusion occurred. The goal of the present investigation was to eliminate the residual carbon, void formation, and rough surface morphology associated with traditional Ni and Ni/Si multilayered Ohmic contacts by fabricating an improved Ohmic contact via direct deposition of the intermetallic phase, Ni_2Si, known to be in thermodynamic equilibrium with SiC at high temperatures (900–1000 °C).

2. Experimental

The Ni_2Si (400 nm) metallization was deposited via pulse laser deposition (PLD) on select grade, Si-face, 8° off-c-axis (0001) 4H *n*-type (2.0×10^{18} cm^{-3}) SiC wafers. Prior to metal deposition, the wafers were cleaned in warm electronic grade trichoroethane (TCA), acetone, and methanol, followed by a rinse in deionized water. The Ni_2Si metallization was ablated from a Ni_2Si (99.9% pure) PLD target under a base vacuum of less than 1.0×10^{-6} Torr using a Lambda Physik Complex 205 excimer laser. Depositions were performed with the laser directly focused onto the rotating target at a 45° incident angle. The sample-target separation distance was 10 cm, and the laser fluence was 10 Jcm^{-2} with a repetition rate of 50 Hz. The Ni_2Si films were deposited at room temperature. The Ni_2Si-SiC samples were rapid thermally annealed (RTA) in an AG Associates RTA for 30 s at 700 and 950 °C. Material characterization was performed on the as-deposited and annealed samples. The contacts' electrical quality was evaluated via current voltage characteristics using an HP 4140B semiconductor test system. The contacts' composition, thickness, and interface quality were determined via Rutherford backscattering spectroscopy (RBS) analysis with an NEC Pelletron accelerator using a 2 MeV He^+ ion beam with a scattering angle of 170° and a solid angle of 5.5 msr. Simulations were produced using the computer code RUMP [16]. The contact structure was analyzed by glancing-angle x-ray diffraction (GAXRD) with a Siemens D-5005 powder diffractometer using Cu Kα radiation at 50 kV and 40 mA. Auger electron spectroscopy (AES) was employed to assess elemental distribution within the contact and across the contact-SiC interface. AES analyses were obtained using a Perkin Elmer PHI660 scanning Auger microprobe. A Hitachi S4500 field emission scanning electron microscopy (FESEM) was utilized to assess the contact surface morphology, contact-SiC interface uniformity, and film microstructure. Digital instruments (DI) tapping mode atomic force microscopy (AFM) was used to quantify the contacts' surface roughness.

3. Results and Discussion

The electrical, structural, compositional, and interfacial properties of the PLD Ni_2Si Ohmic contacts to *n*-SiC have been investigated as a function of annealing temperature. The I-V characteristics of the as-deposited and annealed contacts to *n*-SiC are displayed in Figure 1. The as-deposited sample exhibited non-Ohmic behavior suggestive of a large barrier height. Annealing at 700 °C caused no

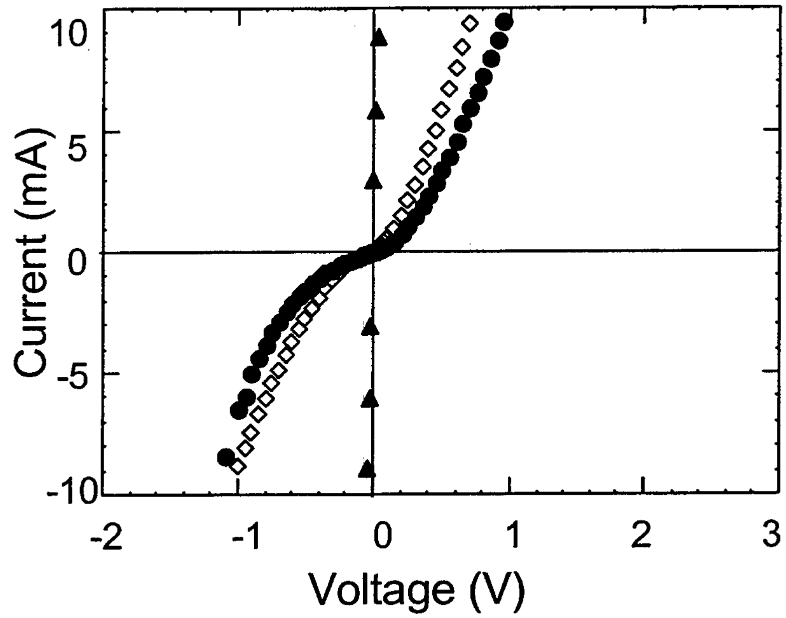

Figure 1. I-V characteristics of the as-deposited (◊), 700 °C annealed (•), and 950 °C annealed (▲) Ni_2Si contacts to *n*-SiC.

improvement in the I-V characteristics. However, annealing at 950 °C resulted in excellent Ohmic behavior, as demonstrated by the I-V characteristics which possess linear characteristics with small resistance and is symmetric with reversal of voltage polarity. Thus, annealing at 950 °C significantly enhanced the current conduction through the contacts.

In order to assess and understand the contacts' electrical characteristics, RBS, GAXRD, AES, and FESEM analyses were performed on the as-deposited and annealed contacts. The RBS spectra for the Ni_2Si-SiC contacts are displayed in Figure 2. The surface energies of the film elements are marked by arrows. The high energy edge of the Si signal from the SiC substrate is shifted to lower energies with respect to that of the Si in the Ni_2Si film because the detected particles that are backscattered there lose energy in the overlying film. From the energy width of the Ni signal, the contact thickness was determined to be ~400 nm. The width of the Ni signal is the same for the as-deposited and 700 °C annealed sample; however, the 950 °C sample is slightly thinner, as indicated by the higher energy position of the back edge of the Ni signal and front edge of the Si signal in SiC. The thinner film, 950 °C sample is due to nonuniformity of the PLD process. Slight variations in film thickness across a PLD deposited film are inherent to the deposition since PLD maintains uniformity on a very small scale, less than 1×1 cm^2 [17].

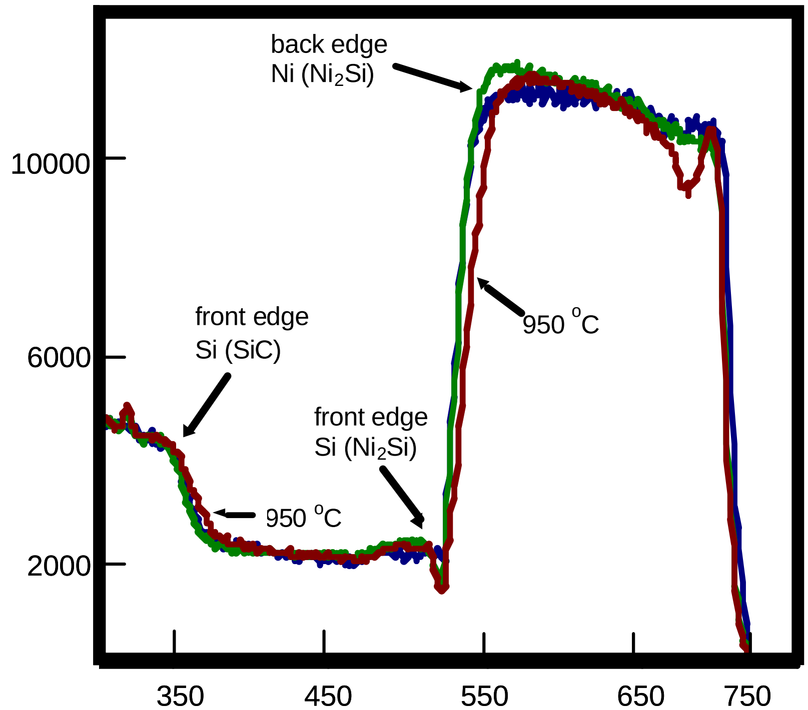

Figure 2. RBS spectra of the as-deposited and annealed Ni_2Si-SiC contacts.

The fact that the back edge of the Ni signal did not shift to lower energies (the width of the Ni signal did not increase) as a result of annealing indicates that there is no increase of the vertical dimension of the contact as a result of annealing. The contact-SiC interface quality was assessed by comparing the slopes of the front edge of the Si signal in SiC and the back edge of the back edge of the Ni signal of the as-deposited spectrum with those of the annealed spectra. The slopes of the as-deposited and 700 °C annealed contacts appear virtually identical; however, the 950 °C annealed contact exhibited a very slight deviation in slope with respect to that of the as-deposited and 700°C annealed contacts, indicating a minimal amount of interaction between the contact and SiC at this temperature. The RBS data also revealed a small amount of oxygen to be present throughout the contact layer for all samples analyzed.

GAXRD results showed the as-deposited contact to be amorphous. The GAXRD data for the contacts annealed at 700 and 950 °C confirmed the presence of the Ni_2Si phase. The AES depth profiles for the as-deposited and 950 °C annealed contacts are displayed in Figures 3(a) and 3(b). The AES elemental depth profile

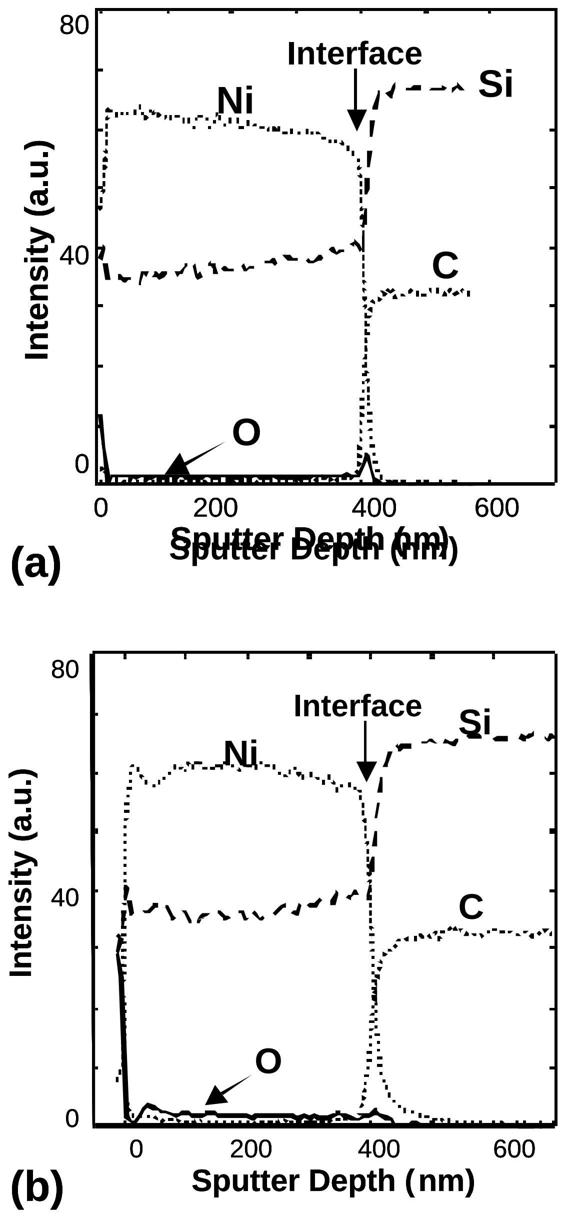

Figure 3. AES elemental depth profiles of the (a) as-deposited and (b) 950 °C annealed Ni_2Si contact to *n*-SiC.

for the as-deposited sample shows a very sharp interface between the contact metallization and the SiC substrate; however, a slight oxygen enrichment is observed at the contact-SiC interface. The interfacial oxygen is most likely due to lack of an oxide etch step prior to the metal deposition. The AES depth profile for the annealed 950 °C sample shows the contact-SiC interface to be fairly abrupt with no interfacial oxygen present. The high temperature anneal (950 °C) appears to have caused dissolution of the interfacial oxide, which in turn

prompted the excellent electrical properties of this contact. The negligible level of the carbon signal within the annealed contact and at the contact-SiC interface indicates that no residual carbon is present within the film or accumulated at the interface as a result of the high temperature annealing process. The absence of residual carbon within the contact metallization is extremely desirable from the standpoint of device reliability. Carbon inclusions at the metal-SiC interface and/or within the contact layer are considered a potential source of electrical instability, especially after prolonged operation of the devices at high temperatures [18]. At elevated temperatures, redistribution of carbon inclusions will arise, resulting in significant degradation of the contact's electrical and microstructural properties [19]. Thus, the direct deposition of Ni_2Si served to eliminate carbon accumulation within the film and at the metal-SiC interface.

Carbon inclusions/segregation are not the only reason for high power and temperature device operation reliability problems. The microstructure of the contact-SiC interface and nature of the contact surface both strongly influence device operational reliability. It has been established that annealing Ni-based contacts on SiC causes extensive voiding (Kirkendall voids) at the original metal-SiC interface, substantial expansion of the contact thickness, and extreme surface roughness [4, 12]. The voids at the interface will cause internal stress and possible delimination of the contact layer, which will compromise device reliability [12]. The internal stress and contact delimination will be significantly amplified under the extreme thermal and electrical stresses typical of the high temperature and high power device operational environments and will ultimately result in device failure. For device applications, Ohmic contacts must be wire bonded to a die package. A rough surface morphology will most likely cause wire bonding difficulty and/or failure under the extreme thermal fatigue during high power and high temperature device operation [4, 11]. Figure 4 displays the FESEM secondary electron cross-sectional micrographs of the as-deposited and 950 °C annealed contacts to SiC. For both the as-deposited and annealed samples, the metal-SiC interfaces were morphologically abrupt, and the contact thickness remained unchanged and uniform over large lateral distances with no evidence of void formation or contact delamination as a result of the annealing process.

Plan-view FESEM micrographs (Figure 5) of the as-deposited and annealed contacts show the surfaces to be homogenous, smooth, and crack and pinhole free. Quantification of the surface roughness was achieved via AFM. The average root mean square roughness values (R_{rms}) for the as-deposited and 950 °C annealed contacts were 0.037 nm and 0.067 nm, respectively. The extreme surface smoothness of the annealed Ni_2Si contact promotes strong reliable wire bonding and will insure maintenance of wire-contact mechanical durability during high power and high temperature device operation.

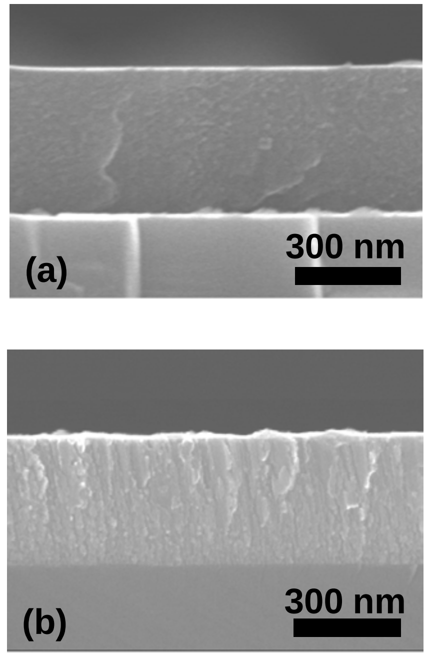

Figure 4. Cross-sectional FESEM micrographs of (a) as-deposited and (b) 950 °C annealed Ni_2Si Ohmic contacts to *n*-SiC.

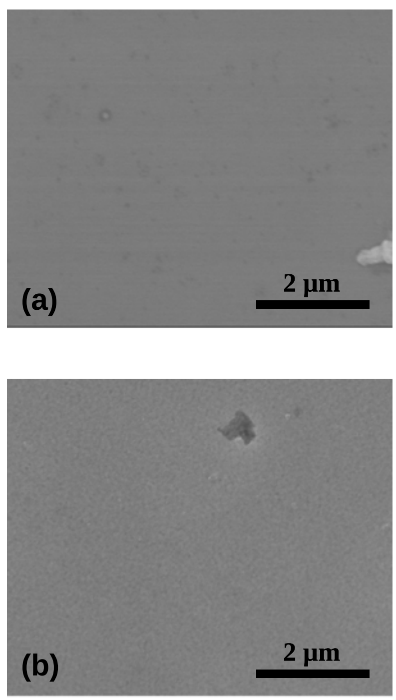

Figure 5. Plan-view FESEM micrographs showing the surface morphology of the (a) as-deposited and (b) 950 °C annealed Ni_2Si Ohmic contacts to *n*-SiC.

Our results have demonstrated that excellent electrical and enhanced structural, compositional, and interfacial properties have been achieved by direct deposition of the intermetallic phase, Ni_2Si, on *n*-SiC. The enhanced contact properties were attained with a minimal number of processing steps with respect to that of Ni/Si multilayer Ohmic contacts [15]. The enhanced material properties and ease of fabrication make this contact attractive for high temperature and high power device applications. Future work will focus on extended static and acute pulsed thermal fatigue testing in order to quantify the thermal reliability of this contact as a function of compositional, structural, and mechanical properties.

4. Conclusions

We have achieved excellent electrical properties for pulse laser deposited Ni_2Si Ohmic contacts on *n*-SiC annealed at 950 ˚C for 30 s. The excellent electrical properties were paralleled by an abrupt void-free contact-SiC interface, retention of the contact width, smooth surface morphology, and absence of residual carbon within the contact layer or at the interface. The detrimental effects of contact delamination due to stress associated with interfacial voiding, and wire bond failure due to extreme surface roughness, have been eliminated for this Ohmic contact. Additionally, electrical instability associated with carbon inclusions at the contact-SiC interface after prolonged high temperature and power device operation has also been eliminated. Thus, the electrical, structural, and compositional integrity of this contact bodes well for its reliability under the influence of high temperature and high power operational stress environments.

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13. ABSTRACT ***(Maximum 200 words)***

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